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LCA FOR ENERGY SYSTEMS

Life cycle assessment of automotive fuels: critical analysis and recommendations on the emissions inventory in the tank to wheels stage

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Abstract

Purpose As new alternative automotive fuels are being developed, life cycle assessment (LCA) is being used to assess the sustainability of these new options. A fuel LCA is commonly referred as a “Well To Wheels” analysis and calculates the environmental impacts of producing the fuel (the “Well To Tank” stage) and using it to move a car (the “Tank To Wheels” stage, TTW). The TTW environmental impacts are the main topic of this article.

Materials and methods Renault’s cars pollutant emissions are measured on the New European Driving Cycle (NEDC) to comply with Euro regulations. The results have been used to show the variability of the emissions in the TTW stage. Five E85 flex-fuel vehicles were also tested to check their compliance with Euro standards, enabling to show the effect of an alternative fuel such as ethanol on pollutant emissions. Finally, Euro standard emission thresholds were transposed into environmental impacts to see how they affect TTW results.

Results and discussion The TTW stage is very significant for the environmental impacts selected. The results show the unpredictable variability of the impacts between vehicles and when switching from gasoline to ethanol (E85). However, this variability is inferior compared with the differences between cars complying with different Euro standards.

Conclusions Measured emissions on a car on NEDC cycle may not be suitable as the input data for TTW calculations. Euro standards associated with average fuel consumptions may be used as the basis for TTW impacts and should be chosen carefully in order to be relevant with the scope of the study. This leads to a functional unit, which is defined as the quantity of fuel needed to move a car that is representative of the average fleet that uses the fuel on 1 km.

Keywords Automotive industry · Euro standards · Fuels · Tank-to-wheels environmental impacts · Well-to-wheels analysis

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1 Introduction

1.1 General context

Until the 2000s, the individual passenger transport was almost exclusively dependent on one resource: oil. Whether it ran on gasoline or diesel, an automobile was solely using crude oil as the fuel for its internal combustion engine (ICE). In Europe, new alternatives (biofuels, synthetic fuels, hydrogen, electricity, etc.) are now emerging for five reasons:

1. the will of the European Union (EU) to secure its energy supplies;
2. the general depletion of fossil resources (especially oil);
3. the high cost of crude oil;

4. the acceptance by both the majority of scientists and the public opinion of the anthropogenic origin of global warming;
5. urban air pollution.

For those last three reasons, these alternatives ought to be more environmentally friendly than fossil fuels.

To assess the environmental impacts of these fuels, life cycle assessment (LCA) is the most appropriate tool. When dealing with fuels, LCA is frequently referred as a Well To Wheels (WTW) analysis, consisting in two stages: the fuel production called "Well To Tank" (WTT) and the fuel use called "Tank To Wheels" (TTW). The building of the car and the road infrastructure are neglected because they are considered identical for all fuel systems (which is true only for vehicles based on ICE). The car maintenance is considered insignificant (Renault, 2009).

To calculate the environmental impacts of WTW emissions, it is necessary to know three parameters: the emissions associated with the production of the fuel, the emissions when travelling a given distance with a car and the fuel consumption of the car. Those three parameters allow calculating the WTW impacts as follows:

$$\Big[\big(\textit{fuel production impacts}\left(\mathrm{MJ}^{-1}\right)\times \textit{fuel consumption}\left(\mathrm{MJ}\cdot\mathrm{km}^{-1}\right)\big)_{WTT} + \big(\textit{exhaust pipe impacts}\left(\mathrm{km}^{-1}\right)_{TTW}\Big]_{WTW}$$

1.2 Scope

This article addresses the issues that can be encountered when conducting a WTW emissions impact study. The numerous issues associated with the WTT stage inventory are strongly discussed in literature (Cherubini et al. 2009, Guinée and Heijungs 2007, Labouze et al. 2008) and this article specifically deals with the TTW stage, though WTT emissions, to a lesser extent, are also studied. When dealing only with CO_2 emissions (for instance when estimating a carbon footprint), the TTW stage is not so much an issue since the only parameters needed are the consumption of the vehicle and the carbon content of the fuel. However, when conducting a WTW impact analysis on numerous environmental impacts, such as acidification or tropospheric ozone creation, the calculation of the TTW impacts requires assessing the pollutants emitted at the exhaust pipe of the car. Different options can be envisaged: in which vehicle is the fuel used? How does the fuel studied affect the car pollutant emissions? How to assess the quantities of those pollutants? This article analyses the influence of using different vehicles with various fuels and recommends values that can be used to correctly assess the TTW environmental impacts in Europe.

1.3 Tank to wheels stage in literature

Numerous WTW analyses for various fuels can be found in the literature. Depending on the scope of these studies, the TTW stage is differently taken into account. Generally, studies dealing with a restraint number of fuels and only focusing on greenhouse gas (GHG) emissions do not include the TTW stage. Such studies have covered numerous fuels: Fischer-Tropsch-based fuels (Van Vliet et al. 2009; Kirkinen et al. 2009), biodiesel (Reijnders and Huijbregts 2008; Achten et al. 2008) and bioethanol (Börjesson 2009; Stichnothe and Azapagic 2009). They have an energy-based functional unit (FU), usually one MJ of fuel produced. Since the scope of these studies is to assess the GHG emissions of an alternative fuel compared to a fossil reference (meaning that both fuels are used in the same engine), the non-inclusion of the TTW emissions is not an issue. The potential decrease or increase of energy consumption by the car and thus CO_2 emissions at the exhaust pipe is usually low (because an engine tends to consume the same energy amount to move the car, whether it is gasoline or ethanol) and thus the TTW GHG emissions are the same, allowing neglecting the TTW stage.

Studies dealing with fuels used in spark ignition engines (SIE) and compression ignition engines (CIE) usually take account of the TTW stage, since CIE tend to use less fuel than SIE for the same distance travelled. Ecobilan PriceWaterHouse Coopers (2002) figures as an exception. The Joint Research Centre/Eucar/Concawe (JEC) consortium study (Edwards et al. 2009) has defined, according to the data submitted by the European carmakers, the fuel consumption of an average SIE, CIE and fuel cell car. These cars have the characteristics of a small family car (because this type of car is the most popular amongst European customers) and their fuel consumption is calculated on the New European Driving Cycle (NEDC; see Materials and methods for further explanations on NEDC). Choudhury et al. (2002) have used the same approach. The FU of these studies is thus the kilometre travelled by an average type of car on NEDC cycle.

For studies dealing with a broader range of environmental impacts, two approaches are generally found: no calculation of the TTW emissions or measuring actual tailpipe emissions. Studies of the first kind include Bernesson et al. (2004, 2006) for first-generation ethanol and Spatari et al. (2010) for lignocellulosic ethanol. The scope of these studies, by neglecting the TTW impacts, is to compare different fuels (ethanol and gasoline) that are used in the same engine and to assess which one is the best. However, by not knowing the significance of the TTW impacts, it is hard to conclude how reliable the differences found in the WTT stage are for the overall WTW environmental analysis.

For the second kind of studies, the TTW emissions are measured for different grades of ethanol (Luo et al. 2009) by using different sources found in the literature or for ethanol and biodiesel by testing two vehicles (Ademe et al. 2010). For Luo et al., vehicles were tested on various Brazilian driving cycles. For Ademe et al., it was decided that NEDC was the best driving cycle to represent the average uses of the cars studied and the only one that would facilitate comparison between studies. Two cars were chosen because they were amongst the best-selling cars in France and their pollutant emissions were considered representative of the car pool circulating in France. These two studies show variations at the tailpipe of the cars studied, implying that alternative fuels could have an impact on emissions in the WTT stage but also in the TTW stage.

This short review of the literature tends to highlight two options for assessing the TTW emissions impacts: measuring pollutants on actual vehicles or trying to represent an average European car. Table 1 sums up the previous paragraphs.

2 Materials and methods

2.1 Well to tank emissions

Although the scope of this article is primarily the TTW environmental impacts, it is necessary to know the WTT emissions in order to assess the significance of the TTW stage. Various databases can be used but for carmakers as for the European Commission (by the intermediary of the Joint Research Centre), the reference for GHG emissions and energy consumption is the JEC consortium study. EcoInvent (Frischknet 2008) and the European Life Cycle Database (ELCD) initiative (Ecobilan, 2008) have also published interesting databases on fuels, with variation between their results. The GREET (Greenhouse gases, Regulated Emissions, and Energy Use in Transportation) model (Wang 1999) as well constitutes a significant database. Because they raise fewer issues than biofuels, only fossil fuels (gasoline and diesel) are studied in the WTT stage here. Indeed, biofuels LCA are highly controversial because of three main methodological difficulties (Labouze et al. 2008). First, energetic crops such as those used for biofuels can lead to land use change (LUC) which can emit GHG. Although direct LUC (e.g. switching a grassland by an energetic crop) effects can be assessed, indirect LUC (switching a food crop by an energetic crop that induce the creation of a new food crop somewhere else) is a methodological and political issue that is yet to be debated. Secondly, the use of nitrogen fertilizers leads to the emissions of nitrous oxide (N_2O) which is a powerful GHG. Since the methodologies to assess these emissions are not consensual, this can strongly affect the results of the LCA. Finally, the production of biofuels generates several coproducts whose impacts are complex to allocate. Energy, economy and mass allocation lead to very different results while coproduct substitution methods are too difficult to be applied.

Because it is a reference shared by both Renault and the European Commission, it was decided to use the data contained in the JEC consortium study to calculate the WTT emissions. These data contain GHG emissions and fossil and renewable energy consumption for every stage of the fuel production but do not describe local pollutant emissions. These were calculated using the EMEP/EEA[1] register for atmospheric emissions associated with combustion (which represent the majority of atmospheric emissions) and ELCD and EcoInvent for the other emissions. Such an approach has already been explored by Ademe et al. (2010) by combining linear programmed coproduct allocation as developed for JEC study with EcoInvent database and new data for the French biofuel market. Figure 1 shows for instance how crude oil extraction has been calculated here. Crude oil consumption is calculated using JEC data, natural gas flaring using Elvidge et al. (2009) and other products (mainly organics and inorganics) using EcoInvent. CO_2 emissions are calculated using the carbon content of oil and gas, pollutants coming from the engine and the flare are based on EMEP/EEA and aquatic emissions are from EcoInvent. Fuel transportation distances have been calculated using Google maps and Worldportdistance.com.[2] The extraction areas of crude oil importations come from Eurostat latest values (2008). For flared gas associated with crude oil extraction, JEC values were not used. Instead, recent data were extrapolated from Elvidge et al. (2009). Importations of diesel fuel from Russia have been considered, though Russian refineries were modelled the same way as the European ones, due to a lack of data. Figure 2 shows the generic pathway of the production of a fossil fuel, with distances and databases consulted. This consists in four stages: extraction, refining, storage and refuelling stations (storage and refuelling stations of gasoline emit volatile organic compounds because of evaporation). Diesel importations from Russia account for 14% of EU consumption (Eurostat 2007).

[1] European Monitoring and Evaluation Programme/European Environmental Agency, http://www.eea.europa.eu/publications/emep-eea-emission-inventory-guidebook-2009

[2] http://maps.google.fr, http://www.distances.com/

Table 1 Emission inventories required to conduct a WTW environmental analysis depending on the scope of the study

Scope of the WTW study	WTT emissions	TTW emissions
GHG, fuels used in the same engine	Required	Not required
GHG, fuels not used in the same engine	Required	Consumption of the engine required
Various environmental impacts	Required	Consumption and pollutant emissions calculated or measured for all engines

A Monte Carlo analysis was conducted, using GaBi software's functionality.[3] Various parameters were used with different standard deviations:

- distances of oil supplies. Standard deviation was calculated with a geographical information system according to the location of the various oil fields and exportation places and the distances between EU countries;
- origin of oil supplies. Data from 2000 to 2009 were used to assess the variability of oil importations in the EU;
- sulphur and carbon contents of fuels;
- emissions associated with combustion, using uncertainties given by the EMEP/EEA register;
- emissions due to flare gas during crude oil extraction.

This Monte Carlo analysis was used to calculate standard deviations associated with the results.

2.2 Driving cycles

To assess the pollutants emitted by a car, it is necessary to use a specific driving pattern (called a driving cycle) combined with a pollutant analyzer. The driving cycle must be precisely defined because the pollutant quantities change according to the driver behaviour (for instance hard or smooth acceleration, speed or gear changes). Each driver has its own driving habits, leading to low emissions for eco-driving or high emissions for drivers stuck in traffic jam, driving at high speed, etc. In order to represent these habits, two sets of driving cycles are generally used in Europe: the NEDC cycle and the Artemis cycles. The NEDC cycle has been defined to represent the average driving pattern of a European driver and consists of four urban cycles followed by a road cycle. It is used to check the compliance of the pollutant emissions to the regulations and to calculate the consumption and CO_2 emissions of every car model sold in Europe. Artemis cycles are designed to represent various driver habits: urban, road, motorway and traffic jam (Boulter and McCrae 2007). They can be considered more representative than NEDC for those specific uses. However, since it is required by the Euro regulations, NEDC is usually much more studied and can be considered as the official cycle representing European driver habits and an approved basis for LCA dealing with the automotive industry (Koffler and Rodhe-Brandenburger 2009). For this reason, only NEDC is considered in this article, though Artemis cycles are discussed in the Discussion section.

2.3 Renault's vehicle fleet

All cars sold by Renault in Europe have to comply with Euro regulations which define thresholds of pollutants that a car cannot exceed on NEDC cycle. This means that the emissions of each car model is measured, according to Euro standards, which regulate the following pollutants: volatile organic compounds (VOC, mainly hydrocarbons), nitrogen oxides (NO_x), carbon monoxide (CO) and particulate matter (PM). The emissions for all car models sold by Renault in 2008 have been analysed, covering vehicles such as small urban cars to larger family ones. As required by directives 1999/94/CE and 2003/73/CE, the fuel consumption of every car model and their CO_2 emissions must be communicated when they are sold. Therefore, fuel consumption, CO_2 and pollutant emissions were available for all cars models sold in 2008.

2.4 Alternative fuels

To assess the effects of using an alternative fuel, it is necessary to study a sufficient number of vehicles. For this reason, ethanol as E85 (meaning 85% in volume of ethanol and 15% of gasoline) has been studied as is it now commercially available (and widely used in countries such as Sweden or Brazil) on different car models. Five vehicles have been tested on NEDC with Euro4 homologation gasoline (containing no ethanol) and E85 in similar conditions. The five vehicles, named here V1 to V5, represent a range of different vehicles, from an urban car

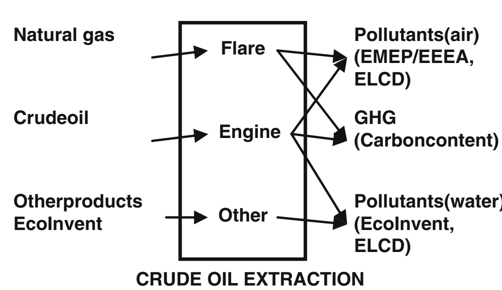


Fig. 1 Crude oil extraction for the WTT stage of LCA

[3] www.gabi-software.com/

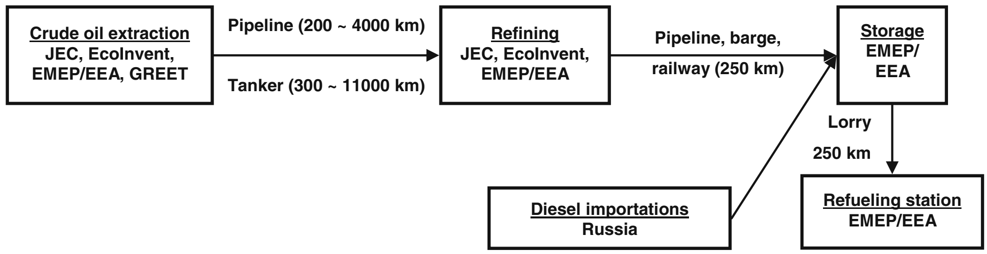


Fig. 2 Production pathway of crude oil-based fuels

to a leisure activity vehicle, that all comply to Euro4 regulations. Only TTW results were calculated (since WTT values for ethanol can be controversial, cf. "Well to tank emissions" paragraph) and environmental impacts were derived from VOC, CO and NO_x emissions (E85, like gasoline, emits marginal quantities of PM).

2.5 Euro standards and the average European fleet

Euro standards have been developed in order to progressively reduce the pollution associated with road traffic. They began with Euro1 in 1993, followed by Euro2 in 1996, Euro3 in 2000, Euro4 in 2005 and Euro5 in 2009. Each of these standards is defined by a European Union directive[4] and Euro6 is due to be implemented in 2014. Euro standards define a set of thresholds for regulated pollutants that a car cannot exceed on NEDC cycle. Emissions thresholds differ between diesel and gasoline-powered cars because those two technologies exhibit different emission patterns: CIE cars tend to emit more NO_x and PM while SIE cars emit more VOC and CO. Table 2 shows the different Euro standards. For diesel cars, no VOC threshold is defined so it was assumed that this threshold corresponds to the VOC+NO_x threshold minus the NO_x thresholds. In Euro standards, VOC are called "HC", standing for "HydroCarbons". However, molecules such as aldehydes or ethanol are measured in the HC category so the term "VOC" has been retained here rather than "HC".

Euro standards only deal with exhaust pollutants and do not set any threshold for fuel consumption or CO_2 emissions. Nonetheless, it is possible to know the average consumption of cars sold in the EU for each year, using Decision 1753/2000/EC of the European Commission enforcing an annual reporting of CO_2 emissions for average SIE and CIE cars. For vehicles after 2008, it is necessary to extrapolate the consumption values, using the current average consumption and the fact that the average CO_2 emissions in the EU in 2020 should be equal to 95 g/km (regulation 443/2009/EC). It is assumed that gasoline and diesel cars will both have average CO_2 emissions equal to 95 g/km (valid hypothesis only if electric vehicles do not represent a high market share in 2020). Table 3 shows the average CO_2 emissions of the average car sold in Europe. The figures in italics are extrapolations. Knowing the period of application of each Euro standard, it is feasible to associate an average consumption to a given level of regulation.

The fleet of passenger cars circulating in Europe is composed of vehicles of different aging. Using Eurostat data, we calculated the aging of the average fleet, which consists of the following ages (in 2008): less than 2 years (14%), between 2 and 5 years (21%), between 5 and 10 years (35%), more than 10 years (29%). Assuming that the repartition has not changed from 2008 to 2010 (which is not perfectly true), the European fleet in 2010 is composed of 7% Euro5, 28% Euro4, 35% Euro3 and 29% Euro2. For 2018, it can be extrapolated that the fleet will be composed of 28% Euro6, 35% Euro5, 25% Euro4 and 12% Euro3.

2.6 Environmental impacts

Human activities can release numerous toxic compounds, leading to a wide range of different pollutions. As described in the previous paragraphs, a car emits CO_2 and mainly four pollutants: VOC, NO_x, CO and PM. SO_2 emissions are neglected because, according to Directive 2009/30/EC, the sulphur content of fuels in the EU27 in 2011 should not exceed 10 ppm. Analyses lead by Renault in 2010 (eight samples of fuel per country) reveal that the average sulphur content in EU27 was around 5 ppm. VOC, NO_x, CO and PM can cause various environmental impacts: acidification (NO_x, SO_2 being insignificant), tropospheric ozone (VOC, CO, NO_x), eutrophication (NO_x) and damages to life (CO, NO_x and PM). Several methodologies exist for the calculation of these impacts. It was decided to use midpoint methods because they are more directly linked with the substances emitted, contrary to endpoint methods which can be harder to analyze and aggregate numerous environmental phenomena. Two methods have been retained: CML2001 (Guinée 2002) and ReCiPe2008 (Goedkoop et al. 2009), which is strongly related to the latter. The impacts mentioned above are thus calculated using CML2001 acidification potential (AP, $SO_{2\ eq}$), CML2001 photochemical oxidation creation potential (POCP, $C_2H_{4\ eq}$), ReCiPe2008 ozone formation potential (OFP, $VOC_{\ eq}$), ReCiPe2008 Particulate Matter Formation Potential (PMFP,

[4] 91/441/EEC, 94/12/EC, 98/69/EC and 2007/715/EC

Table 2 Euro standards for passenger cars (Directives 91/441/EC, 94/12/EC, 98/69/EC and 2007/715/EC)

Pollutant (mg/km)	Fuel	Euro 2	Euro 3	Euro 4	Euro 5	Euro 6
CO	Gasoline	2200	2,200	1,000	1,000	1,000
	Diesel	1,000	640	500	500	500
NO_x	Gasoline	–	150	80	60	60
	Diesel	–	500	250	180	80
VOC	Gasoline	500	200	100	100	100
VOC+NO_x	Diesel	900	560	300	230	170
PM	Diesel	100	50	25	5	5

$PM10_{eq}$) and ReCiPe 2008 Marine Eutrophication Potential (MEP, N_{eq}). Photochemical ozone formation is a complex process involving interactions between CO, VOC, NO_x and meteorological conditions. Under sunlight, NO_2 is dissociated in NO+O and O can react with atmospheric oxygen to form O_3. In the mean time, NO can also react with O_3 to form O_2 and NO_2. Thus, in the troposphere, there is a natural equilibrium between O_3, NO and NO_2, depending on the reaction velocities. However, complex reactions involving VOC and CO can occur, leading to the oxidation of NO to NO_2 and thus shifting the equilibrium towards the formation of O_3. For ReCipe2008, NO_x and VOC play the same role while for CML2001, VOC are preponderant in the calculation of the impact (1 kg of VOC =0.11 kg $C_2H_{4\,eq}$ while 1 kg of NO_x=0.028 kg $C_2H_{4\,eq}$). This difference leads to opposite conclusions when comparing a gasoline-powered car with a diesel one: a Euro4 diesel car (according to Table 2) is more impacting than a gasoline-powered car with ReCiPe2008 while CML2001 concludes the contrary. That is why the two methodologies were retained in our study. No methodology regarding toxicity and ecotoxicity was retained since LCIA models for ecotoxicity and toxicity are still under development and by far not so well established and accepted by the scientific community (as e.g. are the GHG models). Moreover, this would require an extensive study of the VOC composition, for the TTW as for the WTT emissions.

3 Results

3.1 Well to tank results

WTT results are shown for all the impacts described in the previous paragraph. These impacts are compared with GaBi/ELCD results in order to confirm their relevance. Table 4 shows that the results are of the same order as GaBi/ELCD. For gasoline, the differences mainly come from the refining stage because GaBi/ELCD uses energetic allocations for the refinery coproducts while this study uses the same figures as JEC study, which is based on linear programming (LP). LP has been chosen as the best way to deal with the complex processes involved in refineries. It is used by the refining industry as an algorithm describing the processing units, blending facilities, power and utilities of a refinery to design new units, fix the operating conditions, make choices of feedstock or assess the price of oil products. Tehrani Nejad (2007) has also shown that this could be an efficient way to allocate CO_2 emissions associated with the various products of a refinery. None-

Table 3 Average European car CO_2 emissions (gramme CO_2 per kiloometre; from regulation 443/2009/EC)

Year	2000	2001	2002	2003	2004	2005	2006
Standard	Euro2	Euro3					Euro4
CO_2 gasoline	177	175	174	172	170	168	165
CO_2 diesel	160	160	158	158	156	157	158
Year	2007	2008	2009	2010	2011	2012	2013
Standard	Euro4			Euro5			
CO_2 gasoline	162	157	151	145	139	134	129
CO_2 diesel	156	151	145	140	135	131	126
Year	2014	2015	2016	2017	2018	2019	2020
Standard	Euro5	Euro6				Euro7?	
CO_2 gasoline	124	119	114	109	104	99	95
CO_2 diesel	122	117	113	108	104	99	95

Table 4 WTT environmental impacts for gasoline and diesel fuel

Impact	Unit (/MJ)	Gasoline		Diesel fuel	
		Results	ELCD/GaBi	Results	ELCD/GaBi
GWP	g $CO_{2\ eq}$	11 (±6)	17	15 (±8)	10
AP	mg $SO_{2\ eq}$	64 (±16)	92	71 (±18)	60
MEP	mg N_{eq}	7 (±2)	5	8 (±2)	4
POCP	mg $C_2H_{4\ eq}$	6 (±1)	14	6 (±1)	8
OFP	mg VOC_{eq}	65 (±18)	68	68 (±20)	43
PMFP	mg $PM10_{eq}$	18 (±5)	22	20 (±6)	14

theless, the choice of LP can be considered as arbitrary, because no superiority can be proved between LP and energetic allocation (Bredeson et al. 2010). Larger differences can be found for diesel compared with gasoline, because the calculations for diesel differ from GaBi/ELCD on one other aspect: they consider that a part of diesel is not produced in the EU but rather imported from Russia, where the environmental impact of extraction is important (mainly because of oil spills and flared gas). Standard deviations calculated using the previously described Monte Carlo analysis show that gasoline and diesel tend to have a similar impact.

3.2 Variations within vehicles

All regulated emissions measured for Renault's 2008 vehicles have been analyzed and translated into the environmental impacts described in Materials and methods section. Vehicles have been separated between SIE and CIE and between horsepower categories. For each category, the mean has been calculated together with minima and maxima. The results are shown in Fig. 3. In order to represent different environmental impacts on the same figure, WTT impact results for the lowest horsepower category have been set to 100%. WTT impacts for the other categories and WTW results are calculated relatively to this value. For instance, for the average gasoline car whose horsepower is below 60 kW, the WTW stage accounts for 200% of the WTT stage on potential acidification, meaning that WTT and TTW shares are equal (the TTW impacts are simply the WTW minus the WTT impacts).

For gasoline cars, the results show that the TTW stage is strongly significant for OFP, AP and POCP. For diesel cars, the conclusions are the same, except that the TTW stage is significant for all environmental impacts. WTT impacts are increasing with horsepower because of the higher fuel consumption of more powerful cars but, for diesel cars, no correlation can be found between horsepower and TTW environmental impacts. For gasoline, a slight trend towards the increasing of TTW emissions associated with horsepower can be observed. This correlation is strong for AP (R^2=0.92) but weak for the other impacts (0.60<R^2 <0.65). Furthermore, minima and maxima show that the results are highly variable: e.g. the variation is about 200% for POCP on 110–135 kW gasoline-powered cars.

3.3 Variations between gasoline and E85

When switching from gasoline (E0) to E85, emissions at the exhaust pipe tend to change. However, no stable tendency can be identified among the five vehicles studied. Figure 4 shows the results for CM2001 AP and CML2001 POCP. Variations are of the same order as variations between vehicles in Fig. 3.

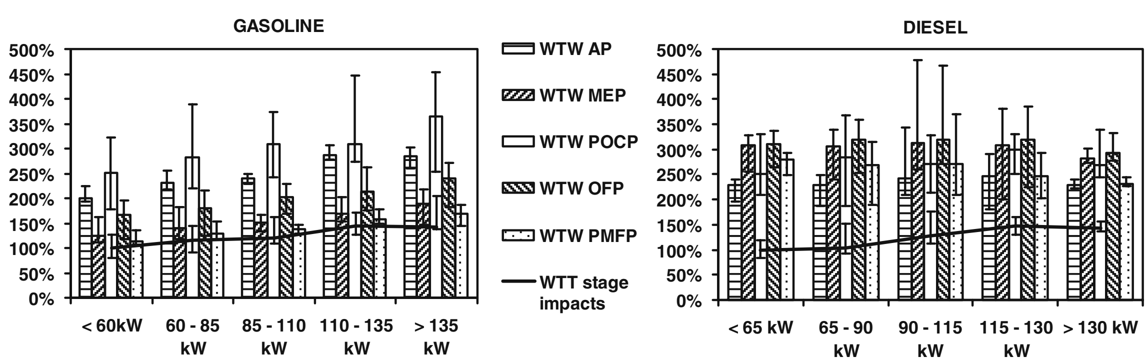


Fig. 3 WTW impacts relative importance compared to WTT impacts for all Renault's car sold in 2008

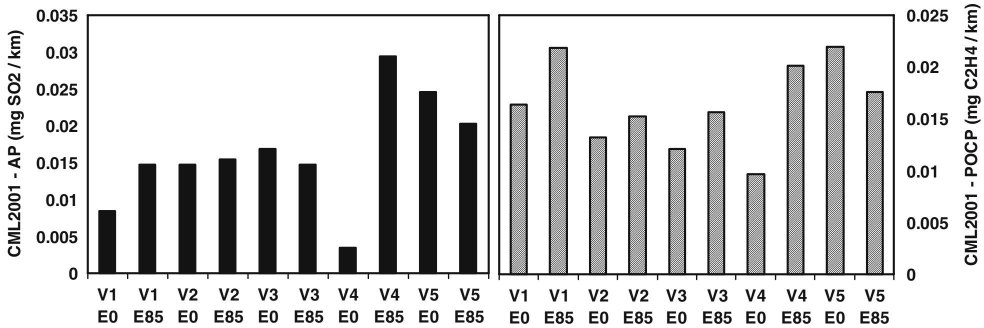


Fig. 4 Effect on NEDC of using E85 compared to E0 for 5 vehicles

3.4 Variations between EURO standards

WTW impacts of gasoline and diesel fuel have been calculated for the average European car, depending on the Euro standard of the car. In Fig. 5, WTT impacts for Euro2 have been set to 100% while WTT impacts for the other Euro standards and WTW impacts are calculated relatively to this value.

Figure 5 shows the very high variability of the results, depending on the Euro standards. Since Euro regulations intend to reduce the exhaust pollutants, environmental impacts decrease as Euro standards improve. However, variations between Euro4 and Euro5 are low, except for PMFP for diesel cars (because of the introduction of the particulate filter). Variations between Euro4, Euro3 and Euro2 are very significant. SIE Euro2 cars are especially impacting on POCP and OFP, because of the high thresholds of VOC while for diesel cars, PMFP is very significant because of the substantial levels of PM10 and NO_x.

Considering the fact that the European average fleet is composed of vehicles that comply to different Euro standards, the results in Fig. 5 mean that the TTW impacts depend on the Euro standards considered and thus of the year of study. Figure 6 shows the impacts of TTW for gasoline and diesel fuel, depending on the year considered. The decrease of all environmental impacts is obviously correlated with the year of study, as Euro2 cars tend to disappear while being replaced with Euro5 and ultimately Euro6 cars.

4 Discussion

4.1 Variation between cars and fuels

Figure 3 shows that no clear correlation can be found between horsepower and tailpipe emissions. All cars comply with Euro regulations but they can nonetheless exhibit very different levels of emissions. Indeed, to comply with the Euro standards, different engines are differently tuned for each car model (leading to a compromise between driveability, fuel consumption and pollutant emissions); that is to say the engine tuning, associated with the aftertreatment strategy, can lead to different emission levels, independent from the fuel consumption. This means that using NEDC emissions of a narrow range of vehicles can lead to miscalculations of the TTW phase. It is not feasible to be sure that the emissions measured on the cars are representative of the average emissions of a broader fleet, since it would require knowing the pollutant emissions of all car models. For gasoline cars, WTT environmental impacts increase with horsepower. This is due to the common fact that, the more powerful the car is, the more fuel it requires. However, no correlation can be found for diesel cars. This is caused by the various aging of the

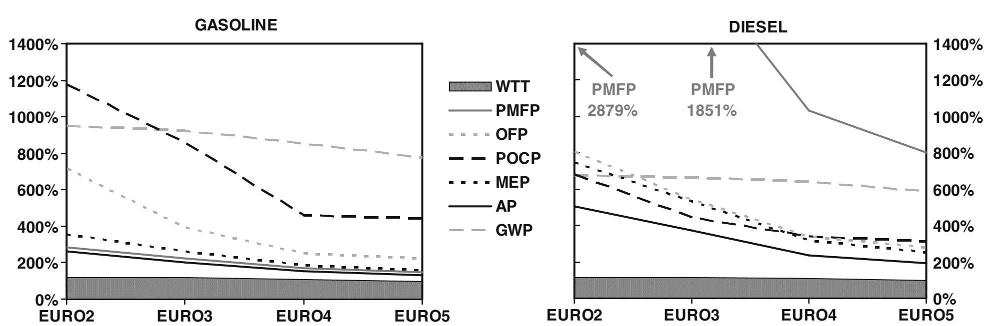
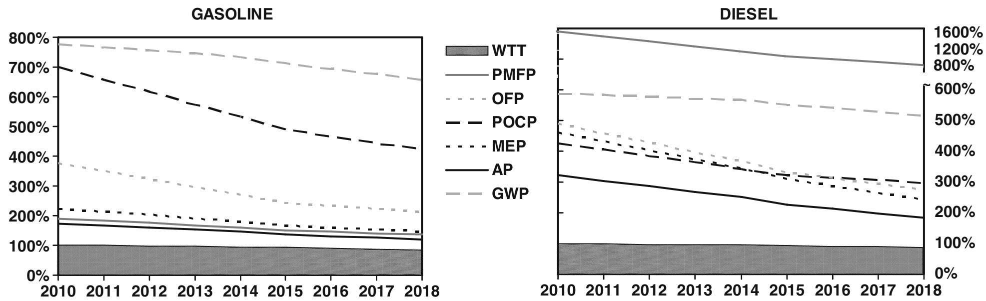


Fig. 5 WTW impacts relative importance compared to WTT impacts depending on Euro regulation (from Euro regulations)

Fig. 6 WTW impacts relative importance compared to WTT impacts depending of the year for the EU-27 fleet (from Eurostat and Euro regulations)



engine, newer engine using less fuel for the same horsepower than older ones.

The same conclusions can be drawn for alternative fuels. Using alternative fuels such as E85 modifies the level of pollutants emitted at the tailpipe while still complying with Euro standards (as shown in Fig. 4). Yet, no stable trend was observed between the different vehicles, meaning that the differences are unpredictable. These differences can be caused by the oxygen content of ethanol, which would lead to more NO_x and less CO emissions. However, these variations are offset by the aftertreatment strategy, meaning that, although the differences in the raw exhaust gas can be predicted, this cannot be applied in LCA. The oxygen content of ethanol also modifies the composition of the VOC emitted: as there is less gasoline, fewer aromatics will be found while unburnt ethanol will be observed. Nevertheless, these modifications of the composition of the VOC do not lead to significant changes in the environmental impacts selected. Nonetheless, ecotoxicity and toxicity impacts, which depend on the composition of VOC, will be affected.

When conducting a WTW environmental analysis, the practitioner should be aware of the scope of his study. If it deals with a narrow range of car models, such as company fleets, the measured emissions at the tailpipes can (and should) be used as the basis for the TTW inventory. However, if the scope is a country or a continent, the actual emissions of all cars cannot be known and thus emissions on a narrow number of vehicles cannot be extrapolated. Furthermore, as the difference of emissions between E85 and gasoline are by far lower than the difference between Euro3, Euro4 and Euro5 cars, they can be neglected.

4.2 Euro standards

For fuels that are or could be used in a wide range of vehicles, such as gasoline, diesel, biofuels (low blending), synthetic fuels, etc., the TTW emissions should be representative of all these vehicles. That is why the FU of such a WTW environmental analysis should be the kilometre travelled with a representative average car, whose emissions may be calculated from Euro standards.

Depending on Euro standards, the TTW environmental impacts share can greatly vary. The magnitude of the variation is far superior to the variations measured between cars or fuels on NEDC cycle. For instance, this means that between Euro3 and Euro4 cars, the variation is far more important than the variations inside the Euro4 group (this is also probably true for other Euro standards). Depending on the year the study is representing, the TTW emissions can thus vary significantly. When conducting the WTW environmental analysis of a given fuel, it is important to have the scope of the study in mind. If the scope is 2010 in the EU27, the WTW environmental analysis should be based on the average European fleet representative of 2010, consisting in various percentages of cars from Euro2 to Euro5. If the study compares future alternative fuels, it is important to take into account that the WTW environmental impacts are decreasing and that WTT and TTW shares vary. The TTW impacts are obviously decreasing with time but the WTT emissions are also decreasing, because of the fewer fuel used for driving 1 km. However, uncertainties on the evolution of the production impacts for crude oil-based fuels might diminish the relevance of this assertion.

5 Conclusions and recommendations

Fuels can be used in a large range of cars, from old ones to more recent models. This is especially true for gasoline, diesel, ethanol and biodiesel (when they are blended with fossil fuels) or synthetic fuels. When conducting the WTW analysis of these fuels, the diversity of the cars has to be considered. It has been shown that even for cars complying to the same Euro regulation, the variability of pollutant emissions is high. This variability is even higher when comparing cars using various Euro aftertreatment systems. Therefore, environmental impacts derived for a representative set of Euro standards should be used for assessing the TTW part. This allows having a FU that is consistent with the scope of a WTW study by representing all the cars that would use the fuel considered and not narrowing the scope of the study to few vehicles. For studies dealing with fuels used in the EU

and whose scope is comprised between 2010 and 2018, the values presented in this article can be used.

These recommendations can be applied when assessing the general WTW impacts of a fuel. However, they do not stand for specific applications, such as comparing various fuels in urban driving, on long road distances, etc. Emissions from the Artemis project or any other measured emissions suited to the scope of the study should be used instead. When conducting a WTW study, it must be kept in mind that there is no way to perfectly represent the car environmental impacts, as the combination of different cars of different aging with different habits can lead to strong variations. These complex variations should be further studied to improve WTW analyses.

Ecotoxicity and toxicity were not included in this study, mainly because of the lack of reliable data on the composition of VOC at the exhaust pipe and the fact that, at the present time, the LCIA methods for those impacts are note widely accepted in the scientific community (as e.g. GWP can be). This field should also be explored to improve WTW analyses.

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Glossary

AP	Acidification potential
CIE	Compression ignition engine
ELCD	European Life Cycle Database
EU	European Union
FU	Functional unit
GHG	Greenhouse gas
GWP	Global warming potential
HC	Hydrocarbons
ICE	Internal combustion engine
JEC	Joint Research Centre/Eucar/Concawe
LCA	Life cycle assessment
LUC	Land use change
MEP	Marine eutrophication potential
NEDC	New European Driving Cycle
OFP	Ozone formation potential
PM	Particulate matter
PMFP	Particulate matter formation potential
POCP	Photochemical oxidation creation potential
SIE	Spark ignition engine
TTW	Tank To Wheels
VOC	Volatile organic compounds
WTT	Well To Tank
WTW	Well To Wheels

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